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A B S T R A C T

Sustainability is high on the agendas of public and private organizations. Governments are setting targets for reducing the use of virgin raw materials in products and to eliminate waste. To accelerate the transition towards a Circular Economy (CE) policymakers are launching instruments. However, policy instruments, such as financial incentives or new regulatory guidelines, are prone to manipulations when the stakes for the involved stakeholders are high. Therefore, policymakers and government authorities need a solid system to monitor and control the implementation and effectiveness of their CE measures. To this end, digital technologies are key to enabling visibility and monitoring of materials flows. They allow governments and other stakeholders to use data to steer the transition towards a CE. However, data from different materials supply chains reside in a diversity of digital platforms used by a diversity of stakeholders involved. Blockchain-based platforms can support the required visibility by combining data from different stakeholders across different materials supply chains. But connecting all data for CE visibility throughout the entire materials flows into one singular platform is unlikely. With the growing number of blockchain-based platforms that each covers parts of data on CE flows, there is a need to assess the level of visibility they offer and to determine which data is lacking to monitor full CE flows. In this article, the development of a framework to evaluate blockchain-enabled information systems on their ability to act as monitoring systems for CE purposes is presented. The design science research approach was followed to develop the framework. Insights provided by academic literature as well as empirical data from three extant blockchain-enabled platforms were used (i.e., TradeLens, FoodTrust, and Vinturas). The evaluation framework can be deployed by public and private actors (e.g., governments and banks) for monitoring purposes, but also by IT providers to offer CE visibility solutions.

1. Introduction

The modern world is under the pressure of dealing with resource exhaustion and environmental destruction threatening its longevity. The root of these sustainability issues lies in the linear economic model established after the industrial revolution as the most efficient way to conduct business. The linear economic model relies on two fundamental principles: easily accessible resources and unlimited earth regenerative capacity (Wautelet, 2018). The economy thrives by consuming ever more planetary resources to manufacture products. These products are later disposed of in the landfills as wastes or are incinerated when they are no longer desirable or useful (Ellen MacArthur Foundation, 2016; Oppen, van, Croon & Bijl de Vroe, 2020). However, such a linear model is not sustainable and leads to resource depletion and environmental damage (Oppen et al., 2020).

In reaction, concepts based on the principle of a circular economy (CE) are presented as an effective response to sustainability issues. This alternative economic model is based on the principles of limiting the use of virgin resources in production systems and eliminating waste streams by promoting a closed resource loop. As such, it aims at reaping the maximum value of produced goods and materials by prolonging their lifecycle. Products are reintroduced to the market upon consumption through value retention strategies, namely: repair, reuse, remanufacturing, and recycling (Ellen MacArthur Foundation, 2016; Ghisellini, Cialani & Ulgiati, 2016; Zeiss, Ixmeier, Recker & Kranz, 2020).

The transition towards a sustainable and circular economy is high on the agendas of public and private organizations. Examples include the Paris Agreement[1] and the European Green Deal.[2] Whereas a lot of efforts

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[1] https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

[2] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

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in the past decade have been directed towards these topics and leading models have emerged (e.g., the CE model of Ellen MacArthur, Foundation[3]), it is now time for action. Governments are setting strict targets and measures and the time window for achieving some of these is quite short. For example in the Netherlands, such targets are to achieve 50% less use of virgin raw materials by 2030 and a waste-free economy by 2050.[4] While such targets are necessary, a key challenge is how to achieve them and how to monitor the progress across sectors and economic activities. And recent examples in the media show that policy instruments that aim to stimulate the CE transition may be prone to manipulations. An illustrative example is a recent case, in which flows that were meant for recycling ended up dumped as waste.[5]

To reach the targets for a CE, businesses, government authorities, and policymakers need increased visibility and transparency in the circular economy flows in order to better monitor and control these (Rukanova, Tan, Hamerlinck, Heijmann & Ubacht, 2021a, 2021b). These activities required data throughout the supply chains of products. Establishing such visibility is a challenging task due to information fragmentation. The data about materials or products is distributed among various actors who may be reluctant to share it (Rukanova, Henningsson, Zinner Henriksen & Tan, 2018, 2021a, 2021b; van Engelenburg et al., 2020).

To this end, new developments like digital infrastructures and platforms enabled by technologies like blockchain, as well as possibilities offered by new technologies such as the Internet of Things and the Physical Internet, offer promising opportunities to create the required CE visibility. But it is very hard to evaluate how they contribute to enabling CE visibility in supply chains, which aspects they cover, and which are missing pieces that still would need to be filled-in to enable CE monitoring, which is essential for steering the CE transition.

In literature, a lot of research efforts focus on the technical aspects of CE (e.g. different methods of recycling) and the development of models to better understand the CE processes (e.g. by the Ellen MacArthur Foundation). And a growing body of research into blockchain-enabled digital infrastructures demonstrates promising results on their ability to ensure data immutability and audit trail which will be key for CE monitoring (Rukanova, Tan, Hamerlinck, Heijmann & Ubacht, 2021b). However, in the current research, there is a lack of understanding of how these platforms contribute to CE visibility.

In a recent paper in one of the top information systems journals, Zeiss et al. (2020) called for mobilizing information systems scholars for CE. Research on how information systems and digital innovations can support CE monitoring is even more limited. A research gap is also recognized by Rukanova et al. (2021a), who propose a research agenda to address the potential of information systems for CE monitoring.

This paper contributes to the identified knowledge gaps by addressing how digital infrastructures can enhance CE monitoring. The main objective is to develop a CE visibility evaluation framework for blockchain-enabled digital infrastructures. Such a framework can be used by governments, businesses, and technology providers to evaluate which data is covered within the digital infrastructure and which still needs to be developed to enable CE visibility and monitoring. This framework can be used to assess extant blockchain-enabled digital infrastructures for CE monitoring. In particular, the framework illustrates which data from multiple platforms needs to be combined to achieve the required visibility.

The remaining part of the paper is structured as follows. In Section 2 the foundational concepts of the research are presented. In Section 3 the design science research approach and the steps followed for the framework development are shown. The resulting evaluation framework is addressed in Section 4, followed by an illustration of the use of the framework in Section 5. Finally, in Section 6 the scientific and societal contribution of the research is addressed. Intermediary results from the framework development process can be found in the Annex.

2. Theoretical background

The objective of this section is to introduce the concepts of digital infrastructures and information technologies to facilitate visibility in the CE flows. These concepts are based on a literature review of supply chain visibility and the use of that visibility for government control purposes (Section 2.1). Next, a brief overview of the literature on blockchain technology follows. Blockchain technologies are promising emerging technologies that ensure the data immutability and audit trail needed for CE monitoring (Section 2.2). In addition, an overview of information tools, such as product passports, is presented as these can provide required data sources in the context of CE monitoring (Section 2.3). These streams of literature provide a basis for understanding the possibilities offered by digital technologies for CE monitoring.

2.1. Digital infrastructures, data pipelines, and supply chain visibility

A Digital Infrastructure (DI) can be defined as a system-of-systems (Hanseth, Monteiro & Hatling, 1996), which transcends organizational and system domains, reducing information fragmentation (Hanseth & Lyytinen, 2010). Digital Trade Infrastructures (DTI) can be seen as specific DIs that focuses on international trade (Rukanova, Henningsson, Henkriksen & Tan, 2016). Among the several DTI initiatives, data pipelines have gained significant attention driven by the idea of capturing business data (bill of lading, invoice, etc.) produced throughout the supply chain to facilitate governmental control (Hesketh, 2009a, 2009b, 2010; Klievink et al., 2012; Pugliatti, 2011; Rukanova et al., 2018). The data pipeline concept is particularly useful, considering that the CE monitoring actors (e.g., policymakers, customs and banks) need to control the CE flows and therefore need access to relevant data.

The data pipeline was conceptualized as a tool that can improve visibility and transparency in the global supply chain by facilitating B2B (business-to-business) and B2G (business-to-government) data sharing (van Stijn, Klievink, Janssen & Tan, 2012). Its efficient operation relies on getting data from the source. In other words, it needs access to the information systems possessed by the various actors involved in the supply chain, such as inter-organizational information systems operated by freight forwarders and information systems used by importers or customs authorities. By accessing this data from the source, it is possible to obtain visibility on information flows scattered across the supply chain and captured in different documents (Klievink et al., 2012; van Stijn et al., 2012).

The actors with a CE monitoring role can leverage the business data by using so-called "piggybacking". Piggybacking refers to using business data for fulfilling different purposes than the original one (Tan, Bjørn-Andersen, Klein & Rukanova, 2011). Data pipelines enable the reuse of business data for governmental control purposes, like carrying out risk assessment and inspections or enforcing compliance. While the traditional data pipeline concept has been developed for enhancing the visibility from the seller to the buyer, recent research proposed the idea for extending the data pipeline for CE monitoring and governance (Rukanova et al., 2021a, 2021b). More specifically, it requires an extension to a) visibility to the processes of production, including visibility on raw materials; b) visibility related to the end of life including reuse and recycling; c) visibility at the border including scanned images and certificates that contain information on the products and their composition.

To understand how visibility can be lost when materials and goods

[3] https://ellenmacarthurfoundation.org/circular-economy-diagram

[4] E.g. see transition agenda for Circular Economy in the Netherlands, https://www.rijksoverheid.nl/onderwerpen/circulaire-economie/nederland-circulair-in-2050 (in Dutch)

[5] https://www.nrc.nl/nieuws/2020/10/16/nederlands-plastic-illegaal-gestort-in-turkije-a4016257

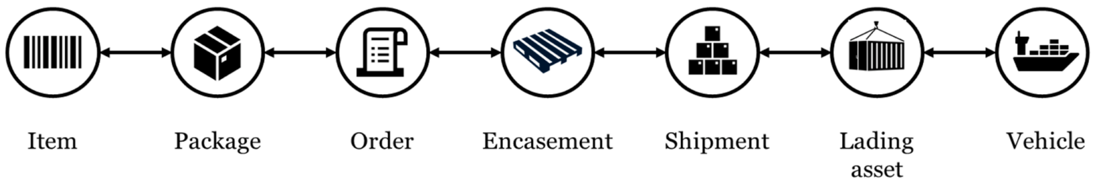

Fig. 1. Entity hierarchy, based on Francis (2008).

Table 1
Information tools.

Information tool	Brief description	Key references
Product passport	Product passports capture information about the components and materials of a product and describe how they can be managed at the end of the product's useful life. An indicative example of a product passport is the materials passport developed in the EU project, *Buildings as Material Banks*.	(Adisorn, Tholen & Götz, 2021; European Commission, 2013; Heinrich & Lang, 2019; Pagoropoulos, Pigosso & McAloone, 2017; Portillo-Barco & Charnley, 2015)
Internet of Things (IoT)	IoT equip objects (e.g., materials or products) with sensors and actuators, converting them into smart objects and allowing them to communicate by creating an information network. Monitoring actors can use IoT to monitor in real-time the status, condition, use, and location of products, identify potential frauds, and consequently ensure the successful implementation of their CE policy instruments.	(Bressanelli, Adrodegari, Perona & Saccani, 2018; Gligoric et al., 2019; Pagoropoulos et al., 2017)
Radio Frequency Identification (RFID)	RFID enables the identification and tracking of a tagged object by making use of electromagnetic fields. This technology can play a key role in CE compliance by facilitating the monitoring of materials and products throughout the supply chain.	(Pagoropoulos et al., 2017)
Product labeling	Product labeling can convey reliable information regarding the characteristics of a product. Today, various product labels focus on informing interested parties about the sustainability aspects of products (e.g., circular characteristics, durability, repairability) or advising them how to maximize their utility. A notable one is the EU Ecolabel attached to products and services that meet high sustainability standards.	(European Commission, 2021; Meis-Harris et al., 2021)

travel in the supply chains, the definition of Francis can be used where he defines supply chain visibility as *"the identity, location, and status of entities moving in the supply chain, captured in timely messages about events, along with the planned and actual dates/times for these events"* (Francis, 2008, p. 182).

An entity is any physical object that transits the supply chain and takes one of the forms suggested by the entity hierarchy (illustrated in Fig. 1). An entity can be an item (e.g., product), a package (e.g., carton), a client's order, an encasement (e.g., a type of packing for the order, such as pallet), a shipment (e.g., different client orders with a similar place of acceptance and place of delivery), a leading asset (e.g., a standardized form of unitizing cargoes, such as containers and trailers) and transport means (e.g., a truck or ship) (Francis, 2008). For simplicity reasons, the focus will be on the four supply chain entities item, package, lading asset, and vehicle as discussed by Francis. In future research, the other elements can be added when needed for CE monitoring.

The entity hierarchy presents in a very straightforward way the loss of visibility about the shipping products when moving towards the higher layers of the hierarchy. For instance, visibility about a product becomes challenging when products are bundled in a carton; cartons form a client's order; orders are packed in a pallet; pallets are combined in a shipment, shipments are unitized in a container; containers are loaded onto a ship (Francis, 2008).

The analysis of the data pipeline concept highlighted its potential for acting as a monitoring system for CE purposes, but only if it is extended to capture lower levels of granularity such as item level and even material composition. And data may be spread across multiple platforms and systems. Furthermore, to control the CE flows and prevent the occurrence of any adverse effects regarding the implementation of their CE policy instruments, the interested actors need to access accurate and reliable business data (Rukanova et al., 2021a, 2021b). Data pipelines can satisfy their needs by providing the original data that companies possess in their information systems about the shipment of goods (Klievink et al., 2012; van Stijn et al., 2012). Nonetheless, a prerequisite to reaping the full benefits of data serving the public good is the need for trust in the data and its quality. CE policymakers need to be sure that the data has not been tampered with and blockchain holds the potential to address their concerns. Therefore, in the next section, the characteristics of blockchain technologies that can satisfy their requirements are presented.

2.2. Blockchain technologies

The rationale behind blockchain is not radical but relies on the old concept of deploying a ledger to store transactions during a time period. Formerly such ledgers were possessed by one single party, like a bank, and managed by an administrator, who could alter the ledger without asking for permission from other stakeholders (DHL, 2018). In contrast, blockchain (a chain of blocks) is a distributed ledger shared across a public or private network of parties that records encrypted pieces of information, called transaction data. Each party in the network has a copy of the ledger. By distributing the ledger, blockchain eliminates the need for a central administrator to act as a trusted party, and updates on the ledger can be done by all stakeholders through a consensus mechanism (Abeyratne & Monfared, 2016; DHL, 2018; Ølnes, Ubacht & Janssen, 2017).

The transition towards a decentralized and distributed system promoted by blockchain can release the data trapped in organizational silos and lead to the development of a reliable CE monitoring system (DHL, 2018). The potential of blockchain is justified by its four unique characteristics: decentralization, auditability, immutability, and smart contracts. These characteristics differentiate the technology from existing information systems (Cole, Stevenson & Aitken, 2019; Saberi, Kouhizadeh, Sarkis & Shen, 2019).

Blockchain can alleviate the stakeholders' concerns regarding data

Table 2
Overview of functional and non-functional requirements for the CE visibility evaluation framework.

Code	Description	Key related references
FRQ.1	The CE visibility evaluation framework should capture the Francis's supply chain entity hierarchy.	Francis (2008)
FRQ.2	The CE visibility evaluation framework should assess the blockchain-enabled data pipelines based on their ability to capture the identity of the supply chain entities.	Francis (2008)
FRQ.3	The CE visibility evaluation framework should assess the blockchain-enabled data pipelines based on their ability to capture the location of the supply chain entities.	Francis (2008)
FRQ.4	The CE visibility evaluation framework should assess the blockchain-enabled data pipelines based on their ability to capture the status of the supply chain entities.	Francis (2008)
FRQ.5	The CE visibility evaluation framework should assess the blockchain-enabled data pipelines based on their ability to capture the events of the supply chain entities.	Francis (2008)
FRQ.6	The CE visibility evaluation framework should extend the supply chain entity hierarchy by including ingredients.	Francis (2008)
FRQ.7	The CE visibility evaluation framework should assess the blockchain-enabled data pipelines based on their ability to capture the condition of the supply chain entities.	Jayaraman et al. (2008)
FRQ.8	The CE visibility evaluation framework should assess blockchain-enabled data pipelines based on their ability to provide visibility from the seller in the exporting country to the buyer in the importing country.	Hesketh 2010)
FRQ.9	The CE visibility evaluation framework should assess blockchain-enabled data pipelines based on their ability to provide visibility in production (including product design).	Rukanova et al. (2021a, 2021b)
FRQ.10	The CE visibility evaluation framework should assess blockchain-enabled data pipelines based on their ability to provide visibility in the flows of secondary raw materials.	Rukanova et al. (2021a, 2021b)
FRQ.11	The CE visibility evaluation framework should assess blockchain-enabled data pipeline solutions based on their ability to enforce compliance at national borders.	Rukanova et al. (2021a, 2021b)
FRQ.12	The CE visibility evaluation framework should highlight the need to work towards blockchain interoperability.	Hardjono et al. (2020); Monika & Bhatia (2020); Schulte et al. (2019); Jin, Dai, & Xiao (2018)
FRQ.13	The CE visibility evaluation framework should guide the monitoring actors to identify the ecosystem of blockchain-based data pipelines.	
FRQ.14	The CE visibility evaluation framework should reap the benefits of available CE information tools.	
NFRQ.1	The CE visibility evaluation framework should be able to illustrate the visibility offered by the blockchain-enabled data pipeline solutions in a simple way.	Usability, derived from Design Science Research Domain.
NFRQ.2	The CE visibility evaluation framework should contain standardized terminology.	Usability, derived from Design Science Research Domain.
NFRQ.3	The CE visibility evaluation framework should illustrate the extent to which a blockchain-based data pipeline serves CE purposes.	Supportability, derived from Design Science Research Domain.

sharing and prevent actors from exchanging inaccurate data (Saberi et al., 2019; Shojaei, Ketabi, Razkenari, Hakim & Wang, 2021). Shojaei et al. (2021) claim that a centralized information system is not an appropriate choice for the collection, storage, and sharing of information due to the existing fragmentation in the supply chain domain. In contrast, they assert that blockchain because of its unique characteristics can incentivize the industry to share its information and to facilitate collaboration among the stakeholders. Therefore, they promote the deployment of blockchain-based CE information infrastructures in the built environment (Shojaei et al., 2021).

An aspect that becomes increasingly important is related to blockchain interoperability. Blockchain interoperability refers to the ability of distinct blockchain platforms to communicate and exchange information with each other, without compromising their unique characteristics, such as irreversibility and traceability (Jin, Dai, & Xiao, 2018). The information exchange should be conducted seamlessly and directly, without the involvement of intermediates to read the information from one source and transfer it to another. Such intermediates can endanger the stored data by manipulating their content consciously or unconsciously (Hardjono, Lipton & Pentland, 2020; Monika & Bhatia, 2020; Schulte, Sigwart, Frauenthaler & Borkowski, 2019). The issue of blockchain interoperability is a pressing challenge in the logistics domain when trying to achieve visibility for CE monitoring purposes (Rukanova et al., 2021c).

2.3. Information tools

To monitor the CE flows and prevent any possible manipulations of the CE policy instruments, the monitoring actors (e.g., government authorities, banks) can receive insights from various information tools available today. Table 1 presents some illustrative examples of such information tools identified in the literature that can enhance CE visibility and increase the monitoring actors' confidence in the environmentally related business data on (the flow of) products.

These information tools provide for capturing information to ensure additional visibility that is relevant for CE monitoring.

The concepts on digital infrastructures, blockchain technologies, and information tools presented in this section are the basis for the development of the evaluation framework. In the next section, the research approach and activities chosen for the framework development are presented.

3. Design science research approach

For the development of the CE visibility framework, the Design Science Research (DSR) approach was chosen. The DSR approach focuses on the development of artifacts with both practical and theoretical importance (Johannesson & Perjons, 2014). Johannesson and Perjons developed the "Method Framework for Design Science Research (MFDSR)": a structured process of research activities to develop artifacts based on a scientific knowledge base for rigor as well as empirical data

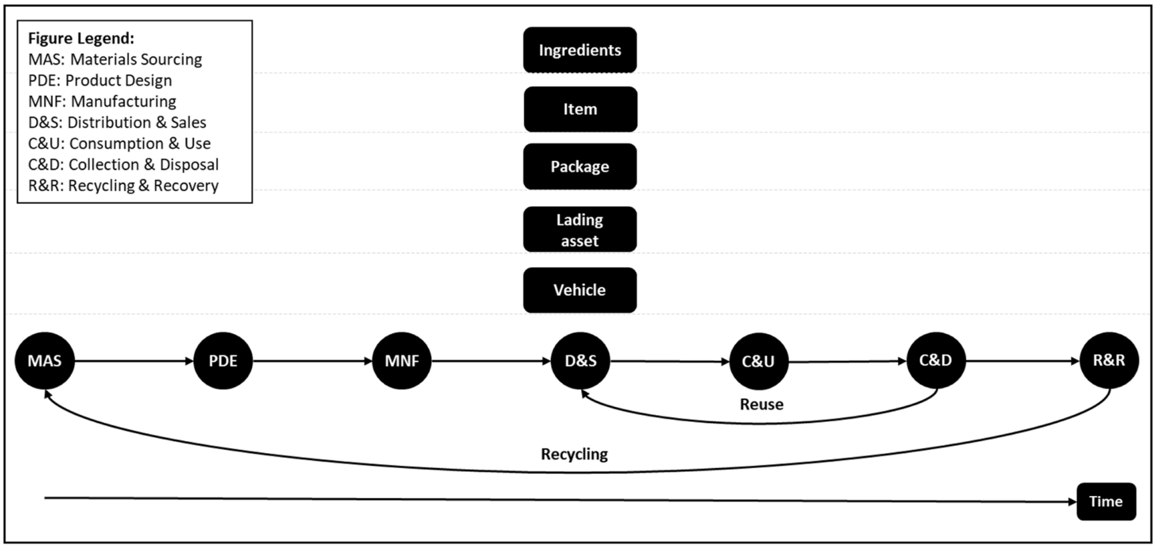

Fig. 2. First building block for the CE visibility evaluation framework: the materials flow.

for relevance (Hevner, 2007). The consecutive activities described by the MFDSR methodology are to *"explicate problem, define requirements, design and develop artifact, demonstrate artifact, and evaluate artifact"* (Johannesson & Perjons, 2014).

For the *explication of the problem* a literature review was conducted on the main concepts of data pipelines, circular economy, blockchain technologies, and supply chain visibility (Doyle, Sammon & Neville, 2016; Hevner, March, Park & Ram, 2004; Peffers, Tuunanen, Rothenberger & Chatterjee, 2007). The findings of the literature review were presented in section 1 to introduce the knowledge gap of lacking visibility in CE flows and in Section 2 to present how data pipelines and blockchain technologies can provide the building blocks for the solution space to address the lack of visibility.

The next research activity was the *elicitation of the requirements* for the CE visibility evaluation framework. A requirement is defined as "a feature of an artifact perceived as desirable by the stakeholders, which can be used for driving the development efforts" (Johannesson & Perjons, 2014, p. 103). Requirements can be classified into functional (FRQ) and non-functional (NFRQ) requirements.

The functional requirements are the functions that an artifact should provide and relies on both the problem at hand and the stakeholders' needs (Johannesson & Perjons, 2014). In this case, the functional requirements refer to the information needed to be included in a blockchain-enabled data pipeline that can be used as a CE monitoring system.

In contrast, the non-functional requirements refer to general conditions and properties, such as usability and supportability of the framework (Johannesson & Perjons, 2014). The sources for the requirements elicitation activity were academic literature on the core concepts of CE, supply chain visibility, and CE policy instruments. In addition literature on information tools that can be used to enhance CE visibility and to incentivize businesses to abandon the linear "cradle-to-grave" economic model was analyzed. In Table 2 an overview of the requirements identified for the development of the CE visibility evaluation framework is presented including the key sources that were used to define them.

In the next research activity of *design and develop artifact,* the requirements were used to develop an initial version of the evaluation framework. Designing the artifact requires decisions regarding its structure and design choices (Johannesson & Perjons, 2014; Peffers et al., 2007). A literature overview on reverse logistics and the concept of a closed-loop supply chain was used to visualize the data needed to monitor circularity. The review led to the identification of the major phases of the materials life cycle: *materials sourcing, product design, manufacturing, sales, consumption and use, collection & disposal* and finally, *recycling & recovering.* In addition, based on Francis (2008) the supply chain entities *ingredients, item, package, lading asset, and vehicle* were added as they represent the physical objects that transit through the supply chain (see Fig. 1). Having data on the materials life cycle phases and the supply chain entities are both crucial for CE monitoring. Therefore, these two elements were combined into the first building block for the framework as visualized in Fig. 2.

Next, in the *design and development artifact* activity the connection to the empirical data for relevance was made (Hevner et al., 2004). Three empirical use cases of extant blockchain-enabled information systems in international logistics were used to iteratively extend the framework. The analysis of these systems yielded empirical insights into the path that materials or products follow from materials sourcing to consumption and during the reuse disposition phase. The chosen uses cases were TradeLens, FoodTrust, and Vinturas.[6]

The first iteration focused on TradeLens, a blockchain-enabled container shipping platform that equips the CE monitoring actors with visibility in cargo flows from source to destination. To offer such visibility, it captures shipment events (e.g., loading a lading asset onto a vessel) and documents (e.g., the bill of lading and packing list). The platform played an essential role in the design phase. In the basic CE visibility framework, it can be noticed that different supply chains are involved in the CE context. That is to say, various shipments of materials or products between a seller and a buyer can emerge, such as the shipment of raw materials from a supplier to a manufacturer. The analysis of TradeLens proved that every shipment can be monitored by having container-level visibility.

The second iteration refined the evaluation framework by studying FoodTrust, a blockchain-enabled platform aimed at transparency and trust in the food system by equipping consumers with rich information about the provenance of food. FoodTrust is a global food network consisting of various businesses interested in reaping the benefits of the platform. Among its first adopters was Carrefour, a French multinational retail company. The company puts data of a plethora of food products,

[6] The research was conducted in the period January- July 2021 and the analysis of the platforms was based on the status of these platforms at that time. Therefore the results need to be interpreted with this in mind, as it is possible that the platforms and their business models evolve over time which may change the CE visibility aspects they are able to cover. If such changes occur, the framework would need to be applied again to identify the new status.

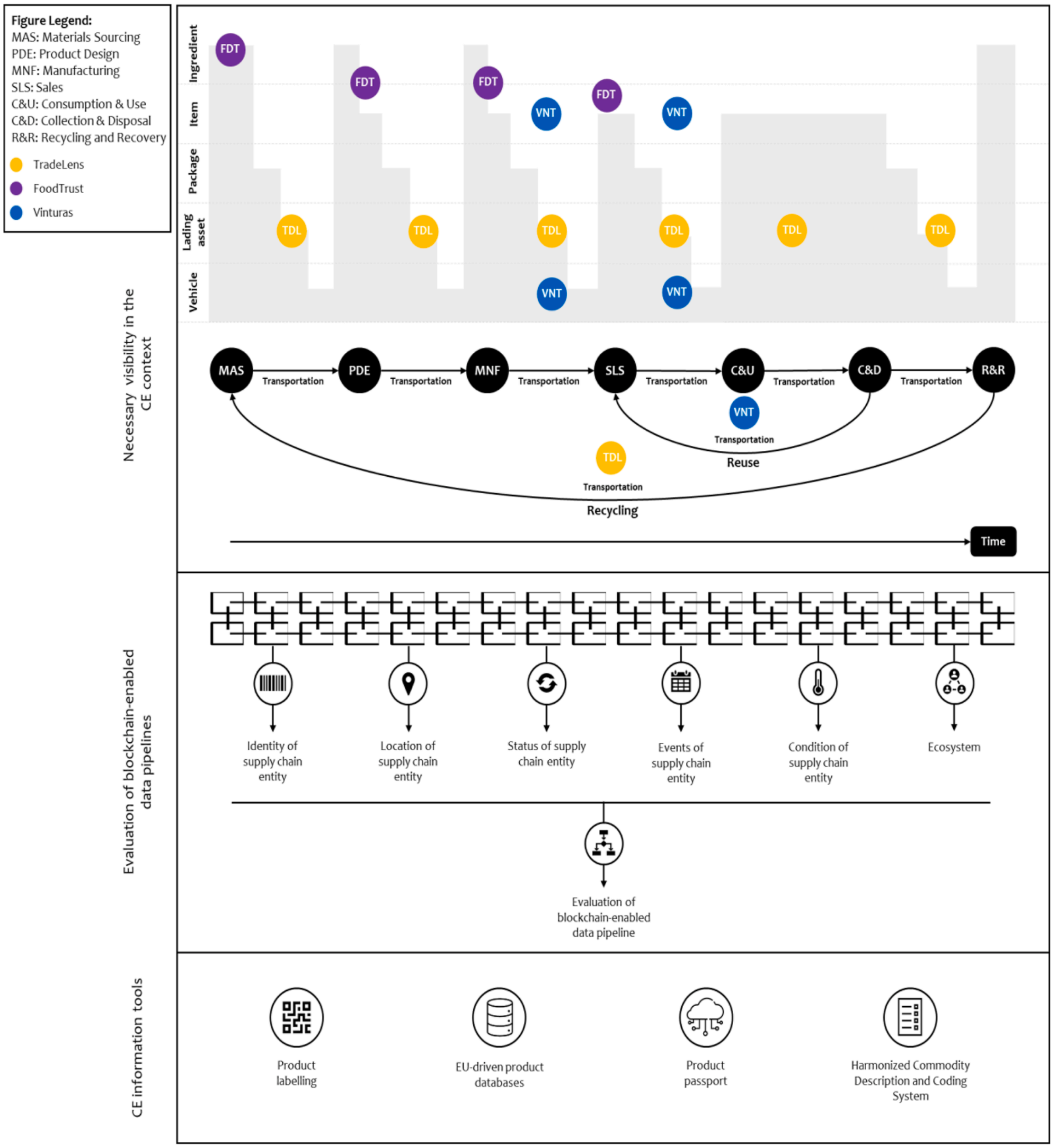

Fig. 3. The CE visibility evaluation framework.

including tomatoes, citrus fruits, infant milk, and mashed potato on the blockchain-enabled platform. For this study, the case of organic textile was analyzed, the first non-food product that Carrefour entered into the blockchain-based platform. The organic textile case illustrated that data on the phases of materials sourcing and product design requires visibility on the level of ingredients. Whereas item-level visibility is needed to monitor the CE processes between the phases of product design and sales.

In the third iteration Vinturas, a blockchain-enabled platform initiated by a consortium of European logistics service providers that operate in the supply chain of finished vehicles, was analysed. Vinturas offers visibility in the journey of vehicles from production to dealer as well as the transportation element of the remarketing of second-hand vehicles. The latter aspect is of great importance for CE monitoring since remarketing resembles the reuse disposition option, where products are directly resold after collection without further processing. Unlike the container-level visibility offered by TradeLens, Vinturas covers the transportation of products (e.g., vehicles) by truck. The unique data provided by the Vinturas platform pointed out that both vehicle- and item-level visibility is required in the transportation of finished products in the CE context.

Each iteration produced an extended version of the CE visibility evaluation framework. The case-specific adaptations and extensions of the framework based on the three cases are presented in Annex 1. The final framework is presented and discussed in Section 4.

The last research activity of *demonstration and evaluation of the artifact* consisted of two parts. First, an expert evaluation was performed to evaluate whether the framework design complies with the requirements that were defined in the requirements elicitation activity. These experts were interviewed during the framework development process. They confirmed the match between the requirements and the framework design. However, they also suggested more research into the product design phase. In the conclusion section this suggestion is elaborated on.

Next, an evaluation was conducted to assess the potential of the artifact for actually monitoring CE flows (Doyle et al., 2016; Johannesson & Perjons, 2014; Peffers et al., 2007). The evaluation took place in the format of a workshop in which a broad set of stakeholders was involved. These stakeholders were representatives from the Customs Administration of the Netherlands, the Dutch Ministry of Infrastructure and Water Management and the IT technology provider IBM involved in the development of blockchain-enabled platforms. The goal of the workshop was to elicit feedback about the usefulness of the framework for CE monitoring for governmental organizations, as well as for technology providers to further develop visibility solutions. A reflection on the findings from the *demonstration and evaluation of the artifact* activity is presented in the discussion section. The next section contains the final version of the framework that was developed based on the design steps presented above.

4. The CE visibility evaluation framework

The CE visibility evaluation framework that was the outcome of the DSR approach is illustrated in Fig. 3. The framework can serve as a support tool for actors, such as government authorities, banks and auditing firms to evaluate extant and future blockchain-enabled information systems on their ability for CE monitoring. The framework can also help technology providers to identify opportunities for expanding their visibility solutions to cover more elements required for CE visibility and monitoring. The framework consists of three layers. A detailed description of each layer is provided below.

The first layer refers to CE visibility. It describes the aspects of a product lifecycle needed to be covered by blockchain-enabled information systems to act as monitoring systems for CE purposes. The product lifecycle starts with the sourcing of raw materials where materials are mined or crops are cultivated to become final products through manufacturing. In between these processes, product design is involved. Product design expresses the design principles adopted in the engineering of products. CE sets design principles to manufacturers, dictating the development of durable, repairable, maintainable, recyclable, upgradable, dismountable, less-resource intensive (e.g., low use of fossil fuels), and non-hazardous products (e.g., free of toxic substances). Upon manufacturing, final products are transported to retailers to be sold to end-consumers or users.

In the CE context, when products are no longer useful or desirable, they can be reintroduced to the market through value retention strategies. The framework depicts two such strategies: reuse and remanufacture. The collection and disposal phase decides the best strategy for the products. If the products do not require further processing, they can be directly resold through a reuse strategy. Alternatively, products can be recycled to enter the raw-material procurement phase. Between each process, the framework shows a transport leg, visualizing the movement of products or materials from one location to another by vessel, truck, or train.

The first layer also illustrates the different supply chain entities involved in the CE context. Building on Francis (2008), a supply chain entity is defined as any physical object that transits the supply chain and takes one of the forms suggested by the following hierarchy:

- *Ingredient:* raw materials used to produce a product;
- *Item:* a final product;
- *Package:* a form of packaging for the item, such as carton;
- *Lading asset:* a standardized form of unitizing cargoes, such as a container;
- *Vehicle:* transport means, such as truck and vessel.

The gray rectangles express the level of visibility required in every stage of the supply chain. For instance, in the production stage visibility on item-level is needed. Moreover, the first layer acts as an evaluation layer enabling the visualization of the visibility (e.g., ingredient, item, package, lading asset, and vehicle) and the parts of the supply chain covered by the examined information infrastructures. That is to say, the CE monitoring actors can use this layer to map a blockchain-enabled information system to see the extent to which they provide the required information for the enforcement of compliance with their CE policy instruments.

The first layer also shows the segments currently covered by TradeLens, FoodTrust, and Vinturas. It can be noticed that none of them covers the closed supply chain, so a combination of them is required to do so. This aspect emphasizes the need to work towards developing blockchain-enabled platforms that are interoperable with each other. In such a way, data from one platform can be connected to the data of another platform for supplementary information. Furthermore, it can be observed that they do not offer visibility on the journey of products from consumption to recycling and subsequently their reintroduction to the market as raw materials. In other words, they do not cover the second product lifecycle. Only Vinturas does cover the reuse disposition option for vehicles.

The second layer shows the type of information needed to be accessed by the CE monitoring actors to reach a conclusion about the potential of a blockchain-enabled information system to monitor the flows of materials and products in the CE context. Building on Francis (2008), they need to access data related to the identity (an identification number), location (the specific position), status (the state), events (changes on the status or the location), and condition (the situation) of the supply chain entities. Furthermore, they need to examine the ecosystem of the infrastructures and their participants. Such insight can facilitate the identification of the sources of the required information. Moreover, in case of any anomalies or frauds concerning the materials flows, they would be able to pinpoint the responsible parties and take corrective actions.

The third layer demonstrates four information tools that can offer valuable insights about the materials or products. Product labeling and EU-driven databases (e.g., EPREL and REACH) can convey information regarding the product design. Product passports are databases that contain information about components and materials of a product, and how they can be disassembled and recycled at the end of the lifecycle. The Harmonized Commodity Description and Coding System (HS) is a nomenclature that facilitates the assignment and collection of import duties and taxes by the customs. HS categorizes all physical goods crossing national borders to a class in a uniform and globally accepted way. Apart from defining the import duties, it facilitates the establishment of legal measures and requirements regarding the products being imported. As such, the HS codes can play an essential role in CE compliance at national borders by enforcing documentation requirements to importers.

The different levels of the framework as described above allow conducting a systematic analysis of available blockchain-enabled platforms and the available level of CE visibility that they offer.

5. Illustrative examples

While it is not feasible here to go into detail in the information provided in all the platforms that were analyzed (some further information on the type of information captured is available in Annex 1), an illustrative example to explain the framework is provided.

First of all, it is clear that the platforms that were analyzed in their current form are largely covering independent streams (e.g., food and cars). There is no immediate value in linking the specific information on a specific supply chain at the moment. However, on a higher level of abstraction, our framework shows that these platforms in principle can provide a complementary level of visibility.

To illustrate: the basic functionality that is offered by FoodTrust may be also used for other types of products. IBM offers Blockchain Transparent Supply (BTS) which is a blockchain-based platform that enables companies to design their own data-sharing ecosystem.[7] This allows

[7] https://www.ibm.com/downloads/cas/BKQDK0M2

companies to define their ecosystem and set up visibility solutions offering similar visibility as in FoodTrust. Hence, it will be possible to capture information about the sourcing of materials, the parties involved in the different steps of the process, as well as certifications obtained.

For example, for organic cotton one can include a certificate proving that the cotton is organic and not genetically modified, when the cotton is made into fabric and the fabric is colored. Other certificates such as the OEKO-TEX standard certificate can be used to guarantee the absence of dangerous chemicals, the safety, and the quality of the fabric. Such information that confirms the absence of dangerous chemicals in products is very useful for government actors who control and monitor the CE flows of goods, e.g., customs, as well as inspection agencies.

Furthermore, for customs and for defining import duties there will be more and more differentiation on the materials used in products and what import duties correspond (e.g., different import duties for recycled plastics), and whether or not certificates will be required. Therefore, such a level of visibility will be beneficial for monitoring purposes. Information about dangerous substances is also useful if the textile is later on reused or recycled in other products. Therefore, this level of visibility will be useful also for business actors acting in the next phase of the circular process.

While the visibility offered by platforms like FoodTrust or BTS is essential when it comes to item-level tracking, when goods travel they are packed in boxes, pallets, containers and subsequently loaded on ships and cross borders. In the logistic process, monitoring actors like customs need to make decisions and conduct risk analysis without having access to the item itself. Therefore, platforms like TradeLens offer additional benefits. As indicated in the framework, TradeLens provides visibility on a container level (lading asset). The use of smart devices on a container (such as an IoT sensor) can capture additional assurances that for example the container has not been tampered with during transport. The trail of assurances from the item level to the container level and back allows for monitoring CE flows and gaining visibility and assurances. Even when the monitoring actors are not in direct contact with the items themselves.

The evaluation framework demonstrates that none of the three blockchain platforms that were examined was able to provide full CE visibility. Achieving such visibility will be a required but challenging task. The evaluation framework allows to open the black box of CE visibility and to explicit information aspects that can be covered to enable CE monitoring from the raw material to recycling. Extant platforms offer partial visibility and hold the potential to extend their functionality by establishing collaborative arrangements (assuming the proper incentives are in place) with other platforms and stakeholders to enable such CE visibility.

6. Discussion

The objective of the research project was to develop a CE visibility evaluation framework for blockchain-enabled digital infrastructures. The framework is intended to on the one hand help CE monitoring actors to evaluate available CE visibility solutions and the visibility that they provide for CE monitoring purposes. On the other hand, it aims to enable IT providers to evaluate which aspects their extant blockchain-enabled platforms already cover, and to assess which are the missing pieces that need to be developed to enable further CE visibility and monitoring. To develop the framework, the Method Framework for Design Science Research was followed, which explicated the steps needed to produce a novel artifact. By executing several activities, the final CE visibility evaluation framework was developed, as presented in Section 4.

By deploying a CE visibility solution, the CE monitoring actors can monitor the flows of materials and products, ensure the effectiveness of their policy instruments, and identify potential frauds. It enables them to stimulate the business actors towards more circular and sustainable business operations and as such to steer the CE transition.

6.1. Scientific contribution

The concept of a CE is an important topic for policymakers, civil society, and academic research. The CE concept has been widely discussed in the literature, starting from the 1960s when the scientific community engaged in discussions about waste and resource management (Zeiss et al., 2020). Nowadays, the CE transition is a well-explored scientific domain. However, it has been approached from a more technical perspective, such as studying the appropriate technologies for recycling plastic.

The research on the deployment of information infrastructures for accelerating the CE transition is a relatively undiscovered domain (Zeiss et al., 2020). While even less scientific effort has been devoted to examining how the information systems that provide visibility in the CE flows can be used for CE monitoring and governance (Rukanova et al., 2021a, 2021b). In practice, blockchain-enabled platforms aiming to provide visibility and to ensure data immutability are being deployed. Still, many of these platforms are developed with different and other goals in mind than for CE monitoring purposes. For actors responsible for implementing CE policies and monitoring of CE it is hard to establish what these platforms can mean for them and what they have to offer.

This research addresses the knowledge gap presented by Zeiss et al. (2020) by developing the CE visibility evaluation framework and contributes to advancing the research agenda for better understanding the use of digital infrastructures for CE monitoring in particular of Rukanova et al. (2021a). The research output is a contribution also to the broader blockchain scientific community. According to Casino, Dasaklis and Patsakis (2019), there is a limited number of frameworks that evaluate blockchain-based infrastructures available in the literature. Exploring the role of blockchain technology in the CE context is a novel scientific domain with a small number of available studies (Shojaei et al., 2021). To the best of our knowledge, the CE visibility evaluation framework is the first one that evaluates blockchain-enabled platforms concerning the CE visibility that they are able to provide.

Another scientific contribution is the concrete evidence provided about the need to work towards blockchain interoperability to monitor and enforce CE compliance. The analysis of the three extant blockchain-enabled platforms highlighted that none of them monitors the full path of materials and products. Every platform covers parts of the CE flows. It is also safe to conclude that there is no system available in today's world that can fully serve CE. A conclusion that emphasizes the imperative need to enable different blockchain-enabled platforms to communicate and exchange information (Hardjono et al., 2020; Monika & Bhatia, 2020; Schulte et al., 2019) or at least enable the sharing of information across platforms. Blockchain interoperability in the context of CE monitoring is a new scientific area, which is worth exploring further since it can unleash the potential of both blockchain and business data.

Additionally, CE visibility was defined to expand Francis's definition of supply chain visibility. Francis defines supply chain visibility as *"the identity, location, and status of entities moving in the supply chain, captured in timely messages about events, along with the planned and actual dates/times for these events"* (Francis, 2008, p. 182). In the CE context, this definition needs to be expanded by pointing out the need to have additional insights into the condition of entities moving in the supply chain. Condition plays a central role in deciding the suitable value retention strategy (e.g., recycling) for a product after consumption. Damages, changes in chemical composition, or other alterations may affect the potential of a product for recycling or direct reuse (Jayaraman, Ross & Agarwal, 2008; NEN, 2007). Therefore, information systems should also monitor the aspect of condition.

The evaluation framework also suggests that the supply chain entity hierarchy, as described by Francis, should be expanded since CE also involves the movement of raw materials (ingredients). The use of the extended hierarchy clarified the level of visibility needed for CE compliance. In addition, CE monitoring actors need insight into the ingredients, items, packages, lading assets, and vehicles transiting the supply chain.

Finally, it was noticed that CE includes several different supply chains, with different actors involved. That is to say, materials or products can be transported in every CE stage, such as from materials sourcing to production and from collection and disposal to recycling. Further research is needed since monitoring the CE flows requires visibility in every distinct supply chain.

6.2. Societal contribution

The framework helps the actors (e.g., policymakers, banks) that have launched policy instruments to promote the transition to CE to fulfill their goals. The CE transition cannot be realized without the active involvement of these actors, both actors drafting the policies, as well as actors such as customs and inspection agencies who monitor the enforcement of CE instruments.

The modern world has been designed to be linear. The linear business model has been established as a profitable way to carry out business. Indicatively, the global economy was nine percent circular, in 2019 (Hartley, van Santen & Kirchherr, 2020). A shift in that mindset requires an external force and policy instruments (e.g., regulations and financial instruments such as taxes or subsidies) can play a steering role. However, such instruments are prone to manipulations when the stakes are high. For that reason, the CE monitoring actors need a monitoring system, which can prevent "greenwashing": false claims regarding the circularity of products for business benefits.

The evaluation framework enables monitoring actors to evaluate blockchain-based information systems on the level of CE visibility that they cover. It also contributes to IT development for CE purposes by explicating what type of information is needed to be included in information systems to be used to enhance CE visibility. More specifically, it supports that such systems need to cover the identity, location, status, events, and condition of the supply chain entities.

Moreover, the framework shows the black boxes: the parts of the CE flows that are not (yet) covered by extant blockchain-based applications. IT developers can use this finding to develop new information systems or improve the existing ones towards providing support to the CE transition.

7. Conclusion

The research on the deployment of digital technologies for supporting CE is considered relatively scarce (Zeiss et al., 2020), and even less attention is paid to how digital technologies can enhance CE visibility for CE monitoring and governance purposes (Rukanova et al., 2021a, 2021b). Therefore, the primary objective of the research was to explore the potential of digital innovations to achieve end-to-end supply chain visibility and support the implementation of CE initiatives, where our main focus was to further focus on the use of CE visibility infrastructures for CE monitoring purposes.

In this paper, using the design science research method and by investigating three blockchain-enabled platforms a CE visibility evaluation framework was developed. The framework aims to be a support tool to assist policymakers, customs authorities, or other actors interested in CE monitoring (e.g., banks and auditing firms) with gaining the visibility needed for better monitoring CE flows. The evaluation framework can be used by these agents to assess the potential of blockchain-based data pipelines to be deployed as CE monitoring systems.

Whereas many blockchain-enabled platforms are currently being developed or are in operation, it is hard for one single platform to cover the visibility needed for CE monitoring purposes. To achieve CE visibility some form of blockchain interoperability or at least some lightweight solution for accessing data available from these platforms and their related ecosystems will be required. This raises governance issues such as how data can be accessed via the different platforms, how identity and access rights can be secured, issues related to incentives for businesses to share data for CE monitoring purposes, as well as issues related to standards and blockchain interoperability.

The current research also has several limitations offering rich grounds for further research.

First of all, our framework builds and expands on data pipeline research, which has a strong focus on logistics processes and movements of goods across borders. Further research can take a different starting point, e.g., the production process and the visibility offered around the production process. Another perspective can bring additional insights to enrich the framework.

Second, as noted in the expert evaluation, the framework did not zoom into the design stage. As product circularity is increasingly incorporated into the design stage of a product, implications for visibility for the later stages in the process are a relevant direction for further research.

Third, the study focused on issues of visibility from the production process to the recycling phase. The issue of how many loops of materials need to be followed for CE monitoring was not addressed. Neither were the conditions under which one traceability process can be completed and a completely new one can start. A topic that raises questions on whether there are sufficient assurances that the secondary raw materials are of such sufficient quality that there is no need for tracing these further to earlier loops and vice versa.

Finally, the research was predominantly focused on digital infrastructures. Internet of things (IoT) and Physical Internet (PI) allow opportunities for sensors and devices to generate data that is relevant for CE monitoring purposes. Future research can target the relationship between blockchain-based digital infrastructures, IoT and PI. Addressing these questions can advance insights on CE visibility for monitoring purposes and the possibilities of digital infrastructures to support these.

Declaration of Competing Interest

To the best of our knowledge the authors are not aware of any conflict of interest.

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Annex 1

The CE visibility evaluation framework based on the literature review conducted on recycling

Fig. A.1

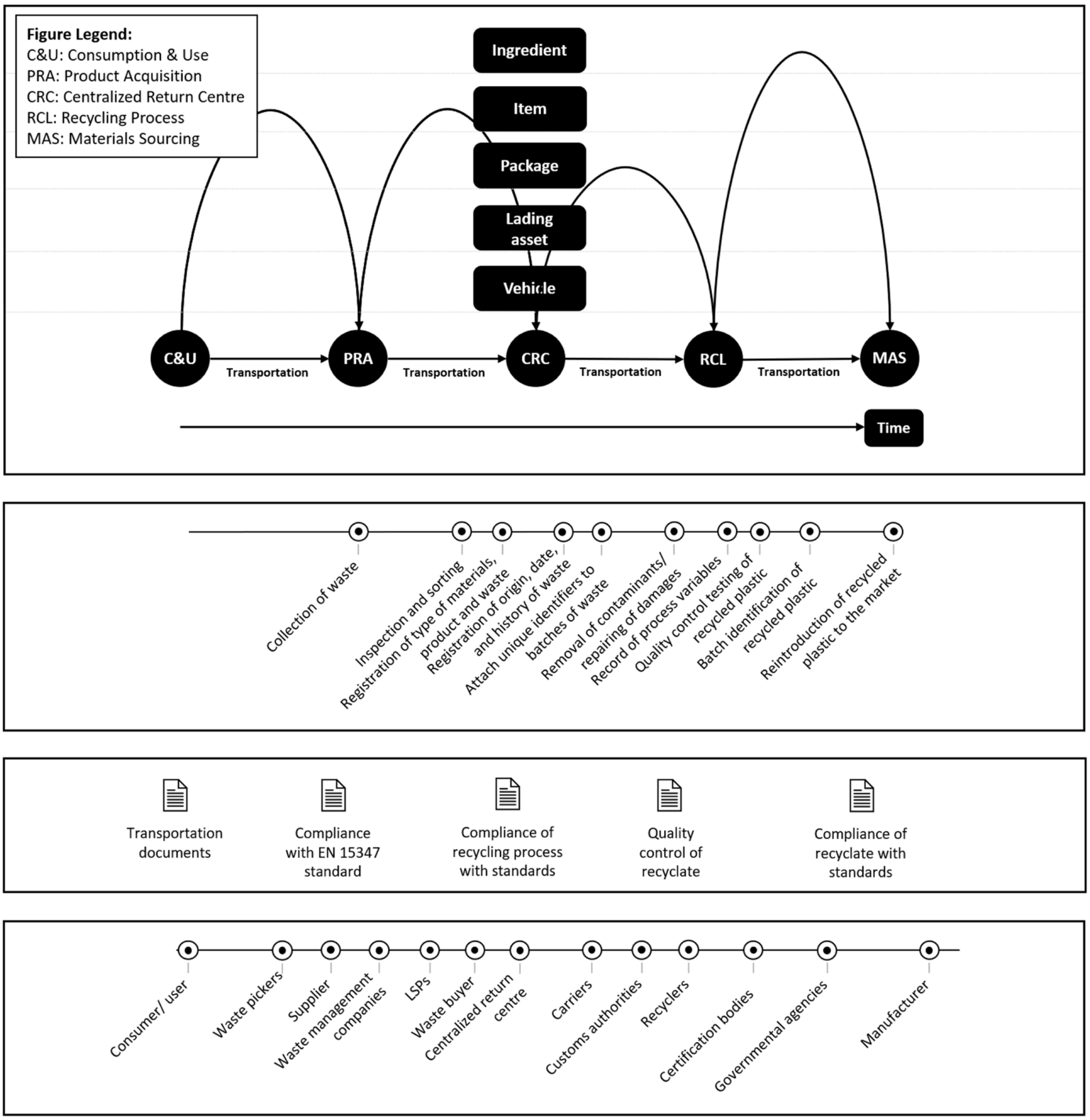

Fig. A.1. The CE visibility evaluation framework based on the literature review conducted on recycling.

The CE visibility evaluation framework based on TradeLens

Fig. A.2

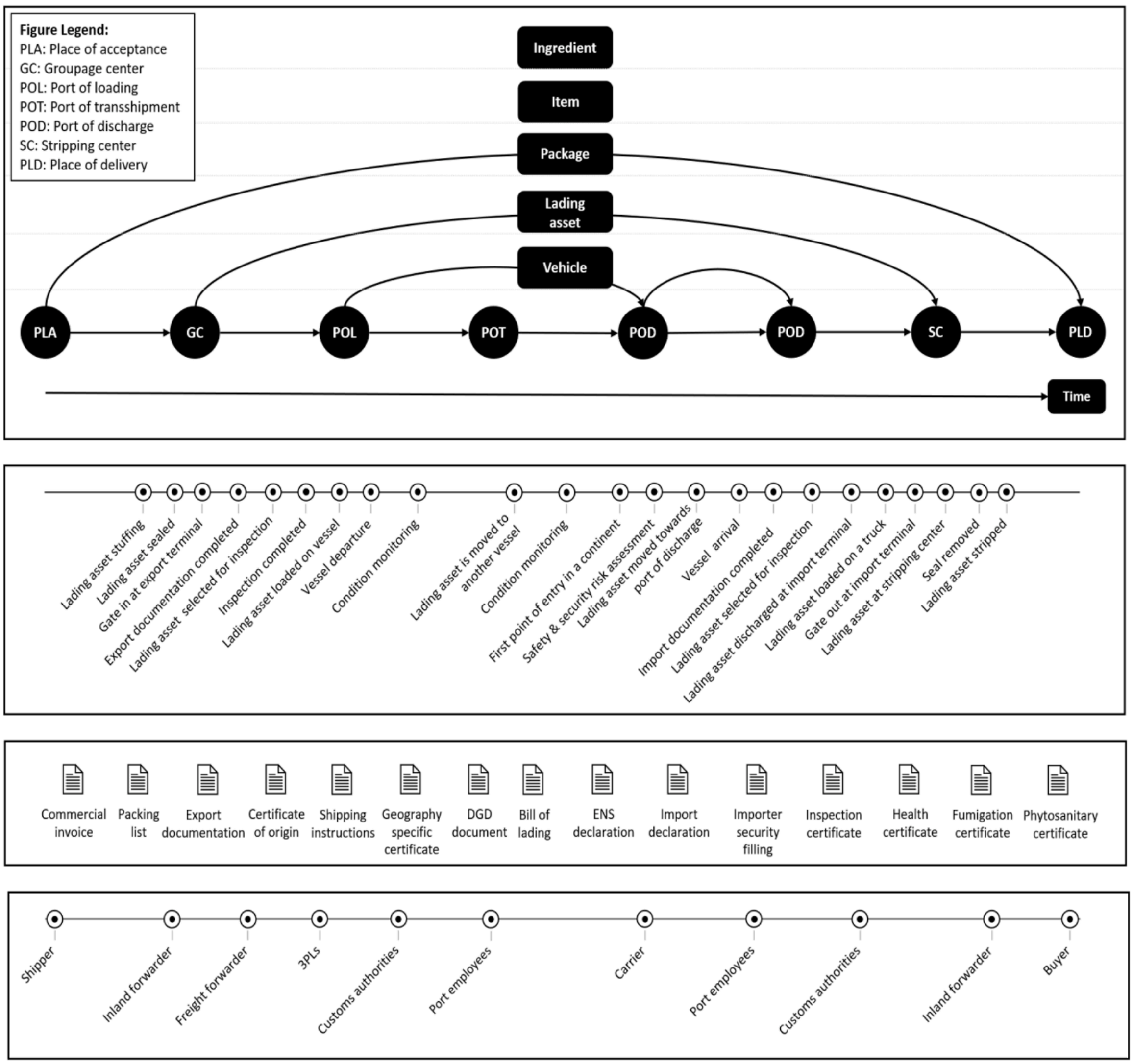

Fig. A.2. The CE visibility evaluation framework based on TradeLens.

The CE visibility evaluation framework based on FoodTrust

Fig. A.3

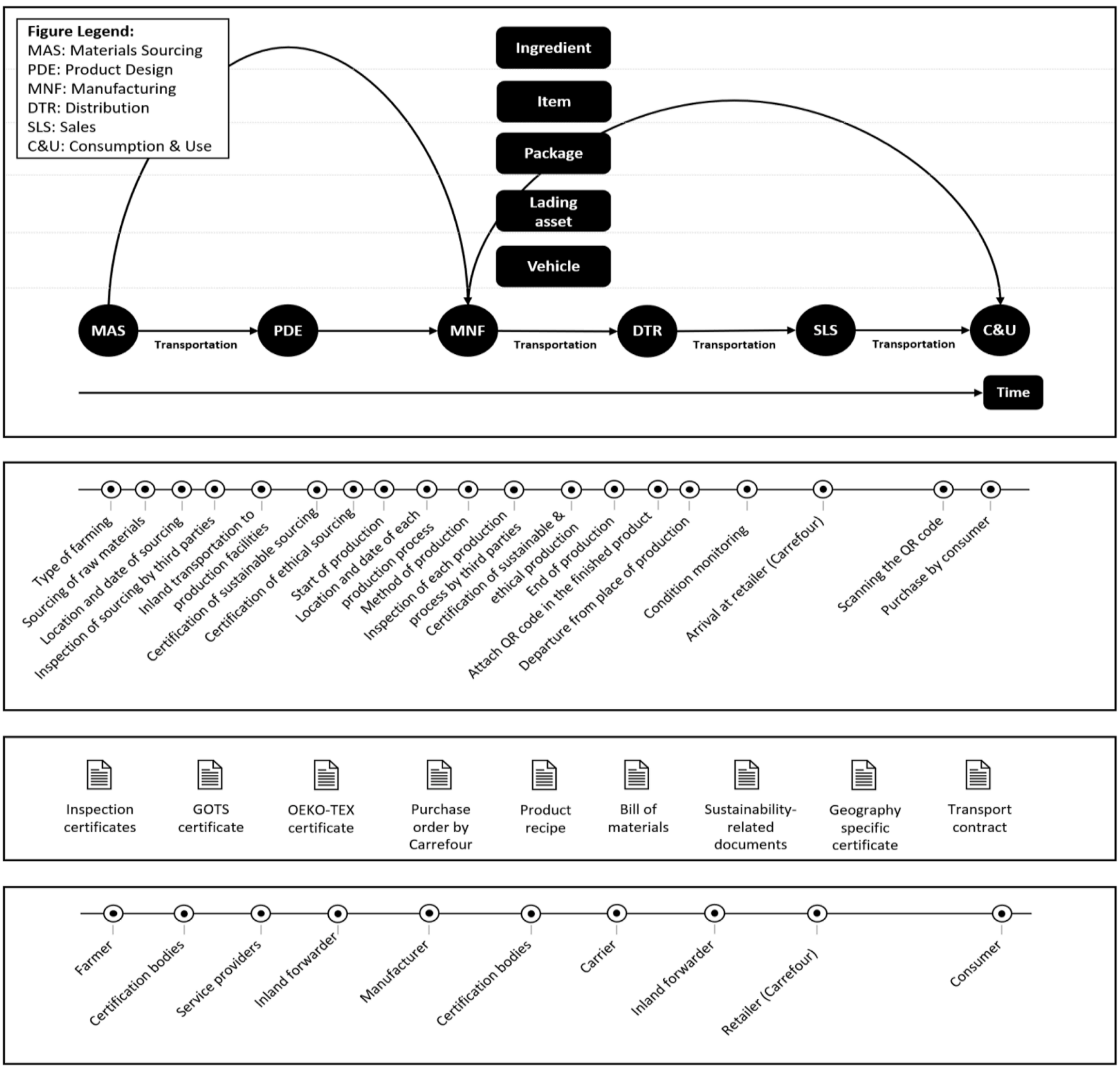

Fig. A.3. The CE visibility evaluation framework based on FoodTrust.

The CE visibility evaluation framework based on Vinturas

Fig. A.4

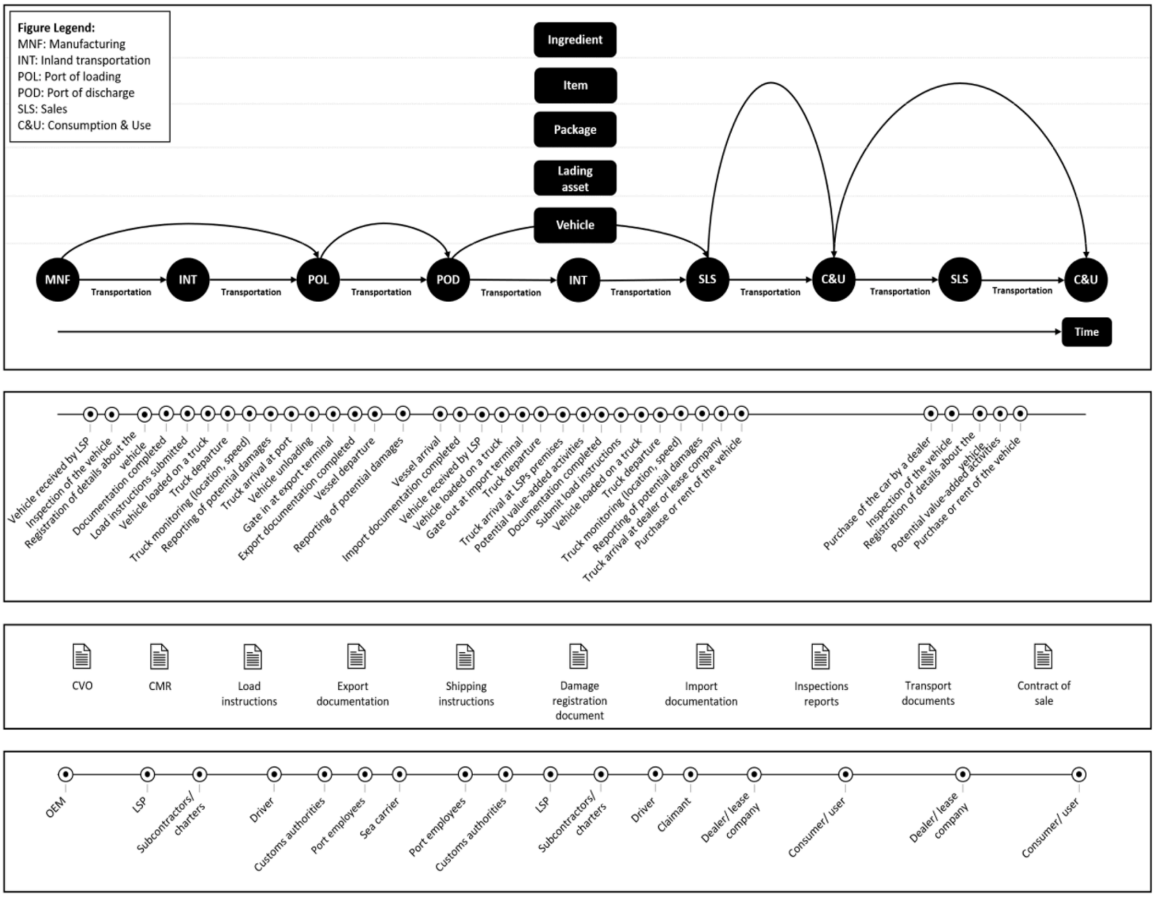

Fig. A.4. The CE visibility evaluation framework based on Vinturas.

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